Simplified charge transfer inefficiency correction in CCDs by trap-pumping

Conference or Workshop Item

Simplified Charge Transfer Inefficiency Correction in CCDs by Trap-Pumping

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ABSTRACT

A major concern when using Charge-Coupled Devices in hostile radiation environments is radiation induced Charge Transfer Inefficiency. The displacement damage from non-ionising radiation incident on the detector creates defects within the silicon lattice, these defects can capture and hold charge for a period of time dependent on the operating temperature and the type of defect, or "trap species". The location and type of defect can be determined to a high degree of precision using the trap-pumping technique, whereby background charges are input and then shuffled forwards and backwards between pixels many times and repeated using different transfer timings to promote resonant charge-pumping at particular defect sites. Where the charge transfer timings used in the trap-pumping process are equivalent to the nominal CCD readout modes, a simple "trap-map" of the defects that will most likely contribute to charge transfer inefficiency in the CCD array can be quickly generated. This paper describes a concept for how such a "trap-map" can be used to correct images subject to non-ionising radiation damage and provides initial results from an analytical algorithm and our recommendations for future developments.

Keywords: CCD, trap-pumping, charge recovery, charge transfer efficiency, proton radiation damage

1. INTRODUCTION

The space radiation environment and "secondaries" from the spacecraft have a negative impact on the performance of electronic systems as a result of the ionising and non-ionising damage. In the case of optoelectronic devices, the loss in performance is primarily caused by incident protons which can form defects within the silicon bandgap. Lattice defects change the electrical properties of the silicon through a number of different processes, including generation (thermal generation of e-h pairs), recombination (charge is captured and is effectively lost) and trapping (charge is captured and released after some period of time)[1]. The impact of these defects is subject to the energy level created within the silicon bandgap, related to the type of impurity forming the defect, the speed at which charge is moving and the temperature of the silicon. The susceptibility of the detector is dependent on the method used to readout the detector, a charge coupled device (CCD) requires a number of charge transfers compared to the one transfer typically required by a Complementary Metal-Oxide Semiconductor (CMOS) image sensor. Making the radiation induced Charge Transfer Inefficiency (CTI) of particular interest for operating a CCD in space, and it is the radiation induced degradation to CTI and a method to mitigate it using trap-pumping that is the focus of this paper.

The process of charge transfer involves manipulating the potential wells formed below the gate electrodes within the CCD pixel, the transfer process being known as 'clocking'. The amount of charge lost during each pixel to pixel transfer is defined by the CTI, and is dependent on the operating conditons[2], *i.e.* the transfer timings, temperature, packet size[3] and the number and type of lattice defects the charge packet encounters. Even before radiation damage, charge transfer in the CCD is not a perfect process, with pre-irradiation values of CTI typically 1×10^{-6} which equates to a charge loss of 0.5% from a 1.6 ke$^-$ charge packet after 5,000 transfers.

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After irradiation with protons, the CTI of an e2v technologies p-channel CCD204 irradiated at 153 K with 1.24×10^9 protons.cm^{-2} was measured using Mn-Kα (~1,600 holes) X-ray events at a density of 1 X-ray event per 80 pixels[4-6] to be 3.6×10^{-5}, using a non-optimised parallel clocking scheme. This would mean that after the same 5,000 transfers 16.5% of the signal would have been lost, with 0.5% being lost after only 140 transfers. It is important to be able to minimise the amount of charge loss, this can be achieved by careful consideration of the operational temperature and timings (i.e. avoiding defects known to be present in large quantities post-irradiation)[2, 6] which is linked to the selection of the material used in the buried channel, i.e. p-channel or n-channel[6-9], the inclusion of a supplementary buried channel[10], a high temperature anneal while in orbit[10] and increasing the shielding to minimise the dose received by the detectors.

However, despite best efforts, as more defects are formed within the lattice the CTI will increase. The amount of increase that can be tolerated is dependent on the application. Therefore it is beneficial to investigate methods of correcting the radiation-induced effects through data post-processing. Substantial efforts have been made in this area to understand the physical process of charge transfer within the detector and develop simulation tools, analytical and Monte Carlo, to attempt to recover the lost charge[3, 11-15]. The use of moving charge forwards and backwards to estimate the CTI was described by Janesick in 2001[16], by using the density of traps measured to estimate the CTI. It has since been suggested that the trap parameters could be used as part of a charge transport model to enable lost charge to be recovered[15, 17-18], two different approaches emerged. The approach described in this paper relies on a simple analytical algorithm to use a trap-map, produced using trap-pumping, to correct X-ray images. The data used during this study was generated alongside a European Space Agency (ESA) funded investigation (TEC-MME/2012/298) into the performance benefits provided through the use of a p-channel rather than an n-channel CCD[4-6].

2. TRAP-PUMPING AND CTI MITIGATION

The principle used in trap-pumping was first developed to identify potential pockets created during device manufacture and is called pocket pumping[16]. A uniform level of charge is input to the image area and then shifted forwards and backwards between rows a large number of times, an example scheme is shown in Figure 1. During which time charges may encounter traps and be moved preferentially from one pixel to another dependant on the specific location and the emission time constant of the trap. The resulting image will contain a number of dipoles which correspond to defects located under the barrier phases, electrodes 1 and 4 in Figure 1. The process of moving charge backwards and forwards is repeated a number of times, after which the CCD is readout as normal. As the charge is clocked forwards and backwards, if a trap is present within volume occupied by the charge it will capture a charge carrier and release it at some point in the future, resulting in a dipole in the subsequent image. The time between capture and release is dependent on the type of defect and the operational temperature, and is described by the emission time constant. Two different applications of the technique have been explored, the first can be used to identify the type of defect[5-6, 19-20] and the second to provide insight into the CTI and provide a simple method of correction[17-18], it the latter method that is the focus of this paper. It should also be possible to utilise the information about defect type and concentration to support a charge transport model which relies on these variables as inputs.

To enable an estimation of the number of traps which will impact charge transfer the clocking scheme used is the same as the one used during normal CCD readout, in Figure 1 this would be integrating under electrodes 2+3 and then stages 1 to 5 to perform a complete parallel transfer into the register. A pause is applied at stage 5 which is comparable to the time required to perform a complete serial transfer, the charge is then clocked backwards from stage 5 to 1 and the process repeated. A trap under electrode 4 will result in the first pixel in the readout direction having lost charge if the emission time constant is less than the time period during stage 5, while a trap under electrode 1 would result in the first pixel in the readout direction gaining charge. The traps under electrodes 2 and 3 will not result in charge being pumped[18]. The process is then repeated a number of times and the amount of signal within the resulting diploes can then be used to estimate the efficiency of charge transfer, an example image is shown in Figure 2.

The resulting image will contain dipoles of different intensities, the amount of charge pumped divided by the number of pumping cycles will give the efficiency at which charge has been pumped. The efficiency is linked to the amount of charge being pumped and the location of the defect within the pixel (the probability that a trap will be encountered) and the type of defect (how long the charge will remain captured). We assume instantaneous trapping. The orientation of the dipole indicates if the trap will contribute to charge loss during normal readout, white pixel first would not contribute as under normal operation the charge would be released back into the charge packet[18].

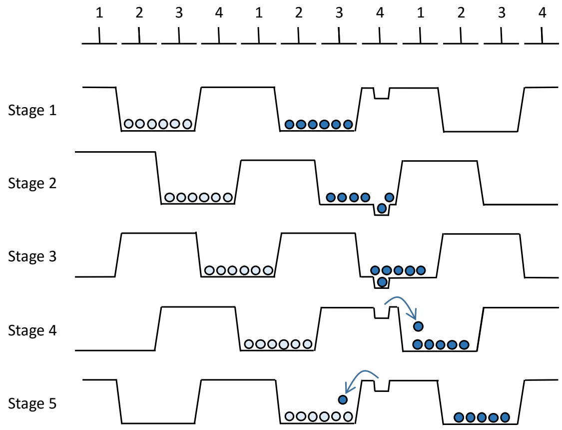

Figure 1. Trap-pumping clocking scheme for a four phase CCD with a trap under electrode number 4. Stage 4 shows the outcome if the charge is released into the original charge packet and in stage 5 the electron is released into the proceeding charge packet.

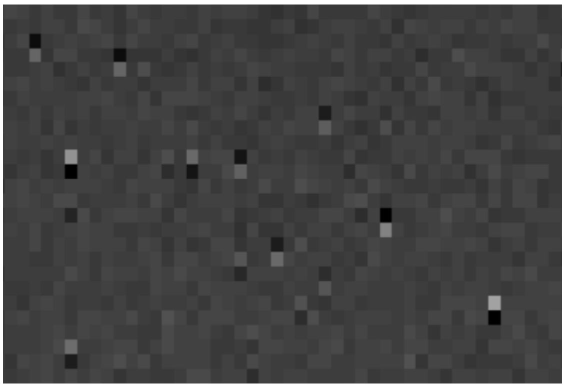

Figure 2. Example trap-pumping image showing the two different dipole orientations and intensities of defects under electrodes 1 and 4

The efficiency at which charge has been pumped is used to create a trap-map, a separate map was created for both dipole orientations, with the efficiency of that dipole located in the respective pixel. An image taken using the same CCD and readout normally can then be moved through the trap-map and events corrected based on the defects individual X-ray events would have encountered when they were read out. If charge encounters a trap that would cause CTI, black first, the amount of charge equal to the efficiency is added to that pixel, for example a trap giving 25% would add 0.25 h^+, a dipole with above 100% is likely the result of two traps. The corrected image should now have a lower effective CTI value than the original un-corrected image, as shown in the Figure 3.

Trap-pumping has been identified in images taken with the e2v technologies CCD47-20 used in the NAVigation CAMeras (NAVCAMs) on-board the European Space Agency's Rosetta space craft[21]. The creation of image with dipoles was inadvertent, as the reason charge was being moved backwards and forwards was in order to suppress surface dark current. Analysis of these images is ongoing and will be published soon.

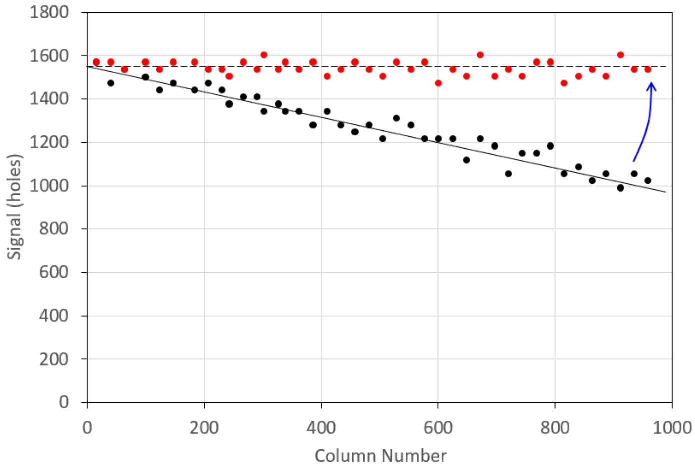

Figure 3. Cartoon showing the ideal recovery, where the signal from each X-ray event is recovered, reducing the charge lost from the solid line to the dashed line, an effective reduction in CTI

3. EXPERIMENTAL ARRANGEMENT AND TECHNIQUE

The irradiation was performed using 7.5 MeV protons from the Synergy Health 5MV Tandem accelerator (UK) with the device held at 153 K[10-12]. The CCD under test was clamped onto a copper cold bench connected to a CryoTiger® refrigeration system with the temperature controlled using a feedback system, comprising a Lakeshore 325 temperature controller, platinum resistance thermometer (PRT), and a heater. An XTF5011/75-TH X-ray tube was used to fluoresce a polished manganese target held at 45° to the incident X-ray beam to provide around one X-ray event per 80 pixels. Two LEDs were then used to provide an optical background of slightly larger than 1,600 h^+, the uniformity of which was measured to be 5%. Clocking and biasing were provided by an XCAM ltd. USB2REM2 camera drive box in conjunction with drive software controlled use a custom MatLab software program. The data used was collected from a CCD204 held continuously at 153 K a period of one week after it had been irradiated with a 10 MeV equivalent proton fluence of 1.24×10^9 protons.cm^{-2} at 153 K.

Three images were collected with trap-pumping having been performed, a further three images were collected with LED illumination but no pumping to allow the background to be subtracted. A threshold of 80 h^+ was then implemented to identify dipoles, the analysis code looked for adjacent pixels that contained 80 h^+ above or below the mean background. This creates the first limitation of the technique, and that is the successful identification of dipoles. However, for inflight applications this is not expected to be an issue because the dose rate is considerably lower than used on ground testing. Therefore the gradual, rather than step change observed in ground testing, formation of defects can be monitored and images subtracted to allow new defects and changes to existing defects to be identified. These images were then used to create a trap-map.

During X-ray image data collection the CCD204 was readout at 200 kHz using a parallel transfer pulse time (t_{oi}) of 1,000 µs. The X-ray images were used a 10 s integration time, with the X-ray tube automatically turned on at the start of the integration time and then turned off 0.3 s before the end of the integration period. The automated X-ray control was implemented to avoid X-rays being incident on the detector during readout, as readout took 22 s. Twenty one images were then corrected using the trap-map and the same CTI analysis code was used to analyse both un-corrected and corrected images. The CTI analysis was performed by dividing the CCD into bins, 30 pixels wide, and the peak location identified by fitting a Gaussian to the Mn-Kα X-ray events within each successive bin. The CTI was then measured using the gradient of the line of best fit applied to the data and the X-ray signal $X(e^-)$, in the form[16]

$$CTI_X = \frac{S_D(e^-)}{X(e^-)n_t} \quad (1)$$

where $S_D(e^-)$ is the average deferred charge, and n_t is the number of pixels transfers.

4. RESULTS AND DISCUSSIONS

The X-ray scatter plot from the un-corrected images is shown in Figure 4, the CTI was calculated to be 3.6×10^{-5}. The X-ray scatter plot from the corrected data, using only dipoles with a dark pixel in the first pixel readout, is shown in Figure 5, the CTI was calculated to be 3.1×10^{-5}. This indicates only a 14% recovery in the CTI, lower than the target value of 90%. The next step will be to consider the process which is taking place during normal readout and how this relates to the observed dipoles and the type of defects which have been identified in p-channel CCDs[5, 8, 22], i.e. how long would defects likely to impact charge transfer remain filled.

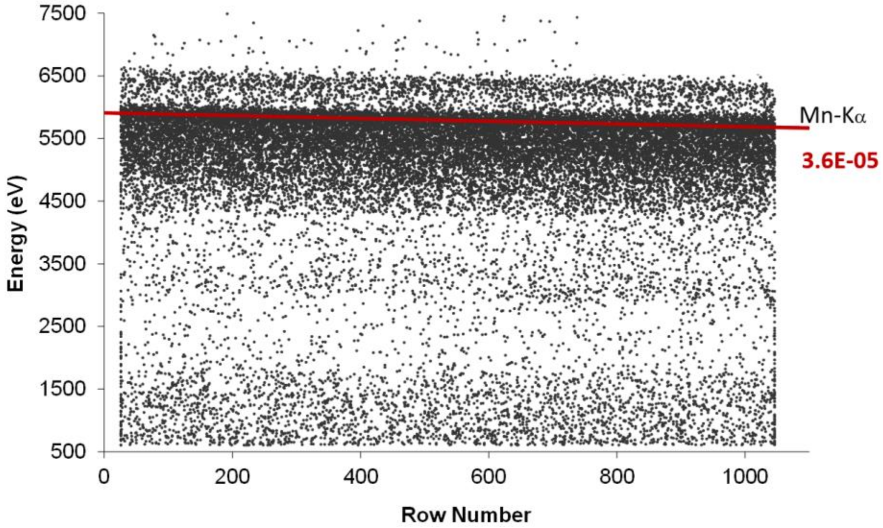

Figure 4. X-ray scatter plot showing data from the un-corrected X-ray images and the resulting fit to that data to calculate a CTI of 3.6×10^{-5}

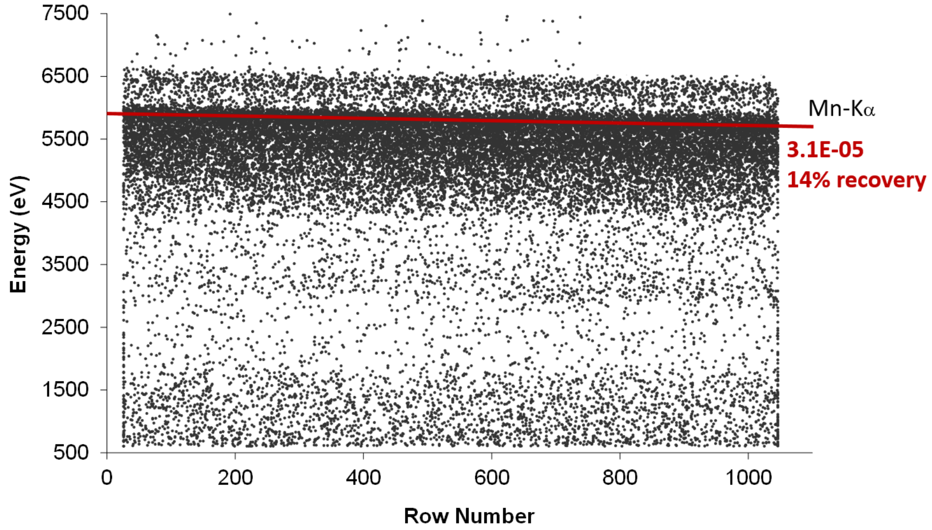

Figure 5. X-ray scatter plot showing data from the corrected X-ray images and the resulting fit to that data to calculate a CTI of 3.1×10^{-5}

The authors are confident that once the type of defects present within the CCD and their impact on the assumptions described in this paper have been considered the effective recovery will be greatly improved. Should this be the case the next step will be to assess the mitigation technique under different operating conditions, different X-ray energies and different fluxes. The opportunity to collect this data will be taken during a side by side n-channel and p-channel CCD irradiation proposed by the authors[22] to ESA which is currently under consideration for funding. The study aims to expand on the additional work proposed by the authors during the original ESA funded investigation (TEC-MME/2012/298) to explore the defect evolution through trap-pumping immediately after irradiation at 153 K and the subsequent impact of the device being allowed at room temperature for various lengths of time before being re-assessed under cryogenic conditions[5-6].

The same camera drive system will operate both CCDs to enable data collection to be performed at the same time with both CCDs. After each temperature change the behaviour of defects in both CCDs will be monitored simultaneously for a period of time (weeks) to determine their type, quantity and stability and the CTI will be assessed. The devices will first be irradiated at 153 K, warmed to 173 K and irradiated again at 203 K, before performing holding the devices at room temperature and 373 K both for a period of 24 hours. This study aims to provide a wealth of information on defect evolution in both n-channel and p-channel CCDs and to compare their CTI to provide a comparison of n-channel and p-channel CCD performance after being irradiated at cryogenic temperatures.

A selection of some of the images taken with the Rosetta NAVCAM over the course of the mission are shown in Figure 6, showing the formation and annealing of defects between December 2007 and February 2014. The traps identified within the NAVCAM CCDs have been used to correct raw images, shown in Figure 7. With such data, very careful consideration must be given to various parameters that affect performance accuracies achieved and this will form part of a future publication focusing on these images and their subsequent correction.

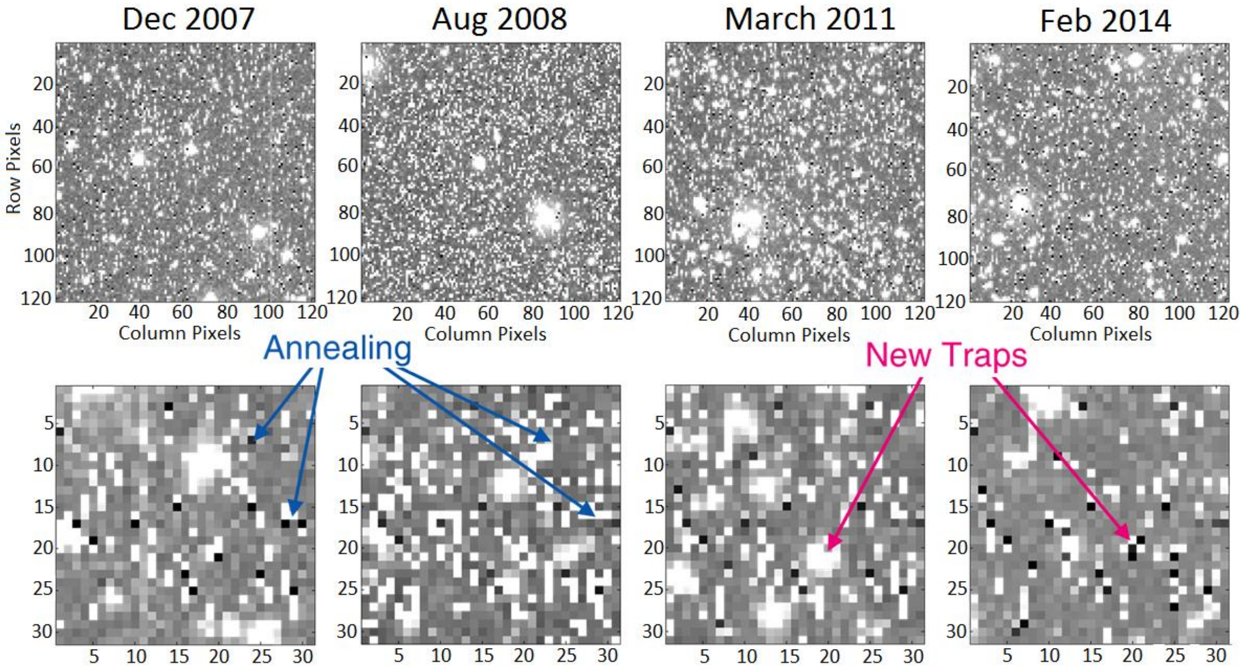

Figure 6. NAVCAM images showing the formation and annealing of radiation induced traps identified during the dither mode clocking operation, image credit ESA/Rosetta/NAVCAM.

5. CONCLUSIONS

The current level of the algorithm has been shown to be fairly effective in recovering the charge lost as a result of radiation damage negatively impacting charge transfer within a CCD. The authors are confident that once the actual defects present within the CCD are considered and their impact on charge loss accounted for a more effective CTI recovery can be achieved. Should this be the case additional data will be collected under different operating speeds, temperature, X-ray flux and X-ray energies. This type of correction should be highly beneficial for extending the operational lifetime of CCDs for use in hostile radiation environments.

It is highly recommended that all future space-based CCD instruments be equipped with a trap-pumping calibration routine. This would allow an ever evolving trap-map to be maintained for ground-based correction algorithms such as we have developed, adapting to changes in levels of radiation damage and any subsequent annealing effects, as we have observed in Rosetta NAVCAM images.

The proposal of a side by side p-channel and n-channel irradiation should provide an excellent opportunity to investigate the defect evolution within both technologies post irradiation, while also providing a comparison of optimised p-channel and n-channel charge transfer. This should help clarify the benefits of both technology types at three different operational temperatures.

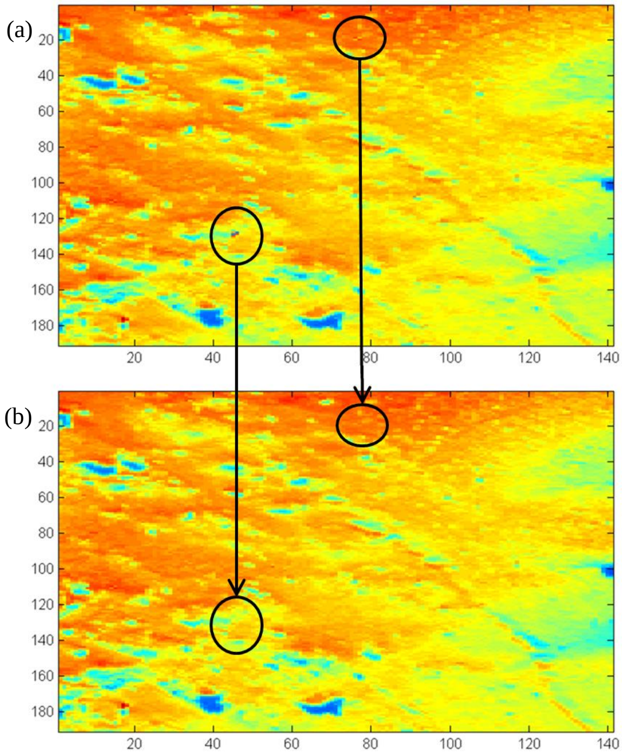

Figure 7. A raw (a) and corrected (b) NAVCAM image section, corrected using the trap-map produced from other NAVCAM images, image credit ESA/Rosetta/NAVCAM.

ACKNOWLEDGMENTS

The authors would like to thank Keith Jones of Synergy Health for his assistance during the proton irradiation, and Ludovic Duvet, Thibaut Prodhomme, Alessandra Ciapponi of ESA for their support during this study.

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